UAV-based L-band SAR with precision flight path control

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ABSTRACT

NASA's Jet Propulsion Laboratory is currently implementing a reconfigurable polarimetric L-band synthetic aperture radar (SAR), specifically designed to acquire airborne repeat track interferometric (RTI) SAR data, also know as differential interferometric measurements. Differential interferometry can provide key displacement measurements, important for the scientific studies of Earthquakes and volcanoes[1]. Using precision real-time GPS and a sensor controlled flight management system, the system will be able to fly predefined paths with great precision. The radar will be designed to operate on a UAV (Unmanned Arial Vehicle) but will initially be demonstrated on a minimally piloted vehicle (MPV), such as the Proteus build by Scaled Composites. The application requires control of the flight path to within a 10 m tube to support repeat track and formation flying measurements. The design is fully polarimetric with an 80 MHz bandwidth (2 m range resolution) and 16 km range swath. The antenna is an electronically steered array to assure that the actual antenna pointing can be controlled independent of the wind direction and speed. The system will nominally operate at 45,000 ft. The program started out as a Instrument Incubator Project (IIP) funded by NASA Earth Science and Technology Office (ESTO).

Keywords: Airborne repeat track interferometry, synthetic aperture radar, InSAR, flight control

INTRODUCTION

Surface deformation measurements at a variety of temporal scales (seconds to decades) are an integral part of NASA's Strategic Plan for Solid Earth Science. NASA's Solid Earth Science Working Group has recommended an observational program that includes both airborne and spaceborne capabilities and this is reflected in the NASA Earth Science Enterprise strategic plan. If feasible, deformation measurements on an hourly basis with global access, would be desired to better characterize and eventually better predict Earthquakes and volcanic eruptions. Very frequent update rates (hours or less) would likely best supported by a spaceborne high-orbit, e.g. high medium Earth orbit (MEO) or geosynchronous, constellation of repeat-track interferometric SAR satellites. Given that the development of such a capability would be expensive, the recommended first step in this observational program is a low-earth-orbit deformation satellite with a repeat period of roughly one week supplemented by a sub-orbital radar program, providing repeat-pass measurements at time scales much smaller than one week, potentially as short as twenty minutes.

Although satellites have been used for interferometric repeat track SAR mapping for close to 20 years, repeat track interferometry is much more difficult to implement from an airborne platform. Several organizations have acquired experimental airborne RTI data, however, without developing a capability to acquire significant amounts of high quality RTI data. The primary reason for this state of affairs is that 1) It is difficult to fly the same or nearly the same pass twice in the air, due to wind gusts, turbulence, etc. and 2) it is difficult to maintain the same antenna pointing on repeated passes due to varying cross-wind, leading to varying yaw angles.

In addition to providing unprecedented temporal detail of deformation of dynamic processes, the UAV/MPV operated radar will be a testbed for understanding the observational needs for how rapid repeat observations would be acquired. This is a capability that the currently operational NASA AIRSAR system has demonstrated but cannot practically support for science experiments in its current configuration due to lack of track repeatability and beam pointing limitations.

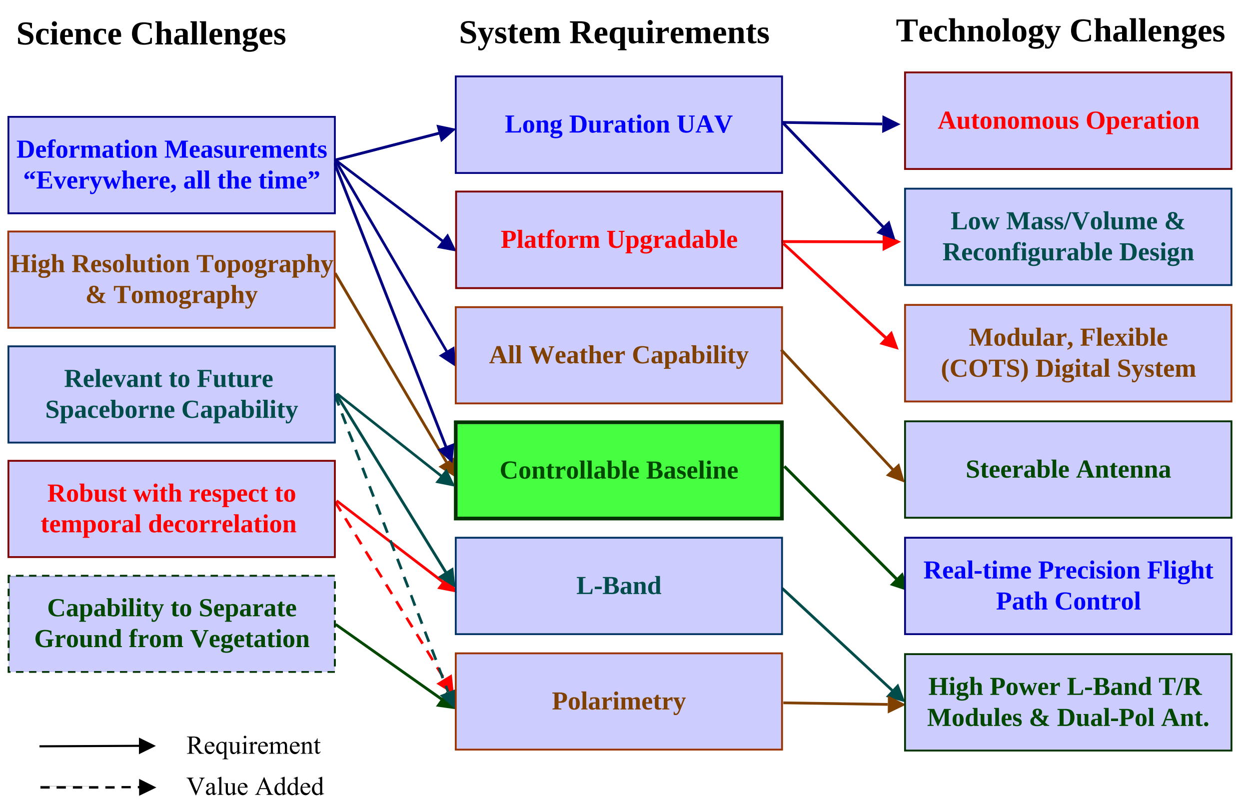
The project started out as a proposal submitted to the NASA 2002 Instrument Incubator Program (IIP) to develop a repeat track measurement capability as an augmentation to the existing AIRSAR system. NASA accepted the proposal but directed that the proposed capability be fielded on a UAV or MPV platform to support the long term interests of the airborne science community. After a year of study and experiments, NASA directed JPL to proceed with a full scale implementation. This paper outlines the status of the project, including a high level radar design.

1. REQUIREMENTS

At a high level, the original requirements for the system being developed, included scientific objectives such as "deformation measurements everywhere, all the time", a capability to also acquire high resolution elevation measurements, providing pathfinder data for future spaceborne missions, and being robust in terms of supporting long temporal baselines and limiting the sensitivity to vegetation. These level 1 requirements were then flowed down to system level requirements and eventually implementation requirements, as indicated in table 1.

These very high level requirements were then expanded to more detailed requirements, as for instance the relevance to future spaceborne missions combined with access to airspace, lead to a requirement for a high altitude platform. More detailed requirements and implementation details are outlined in the following.

Table 1. Simplified high level requirements Flow



2. SYSTEM

Repeat track interferometry not only requires that the phase centers of the radar antenna locations for the individual tracks are approximately coincident, it is also essential that the antenna look directions are identical to within a fraction of the beamwidth. Given that the wind can be substantially different at different times, even if the platform is capable of accurately repeating the desired track, the yaw angle of the platform can vary widely on different tracks. This we intend to mitigate by electronically steering the flush mounted antenna to the desired direction. As such, the UAVSAR system is a tight coupling of platform and sensor capabilities.

Given that the temporal separation of the acquired track will have a wide range, it is required that wavelength is long, which mitigates wavelength level changes in the scene between observations. However, given spectrum availability and the desire at the same time to have the largest possible bandwidth to increase the so-called critical baseline[2], L-band is found to be a very attractive compromise with a quarter meter wavelength and 80 MHz of available bandwidth. Given an assumed operating altitude of 45,000 ft, a near angle of incidence of approximately 30°, and an 80 MHz signal bandwidth –equivalent to a 2 meter slant range resolution, the perpendicular critical space baseline is

$$B_{c\perp} = \frac{\rho\lambda\tan\theta}{2\Delta\rho} \approx \frac{15,800m\ 0.24m\ 0.6}{2\cdot 2m} \approx 600m \qquad \text{(Eq–1)}$$

Although repeat track interferometry will generally work well over flat terrain, even at track separations up to on the order of a 1/10th of the critical baseline, practical effects such as terrain relief, knowledge of local elevations, slopes, and volume scattering will mean that robust RTI performance requires baselines significantly shorter. Based on our analysis a 10 meter residual baseline will be acceptable in most situations, however, “exact” repeats at the 1 meter deviation level would be very desirable.

The radar modifications required to support repeat-pass deformation measurements include:

- Electronic steering of antenna beam with 1° accuracy over a range of ±20° (goal ±45°) in azimuth so that the repeat pass pointing requirements can be achieved for a wide variety of wind conditions aloft.
- Steering of antenna must be linked to the inertial navigation unit (INU) attitude measurements with an update rate capability of less than one second.

The desired flight track and radar electronic pointing capability desired for airborne repeat pass observations are illustrated in Fig. 1.

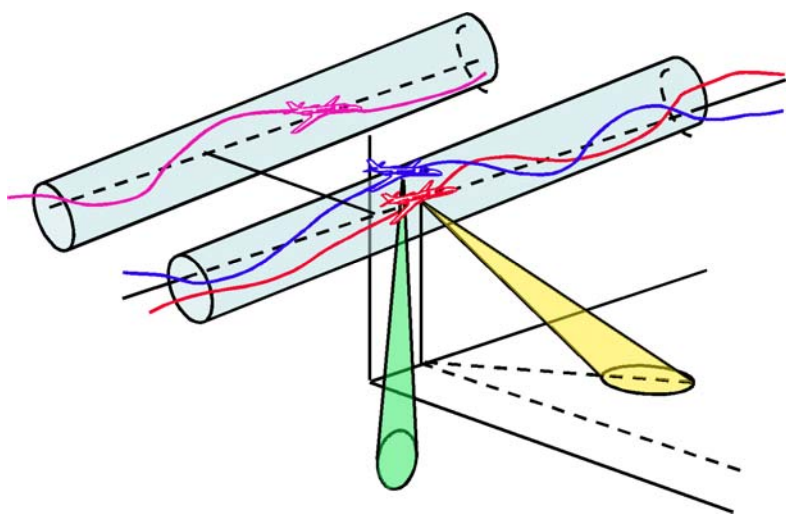


Figure 1. To ensure high interferometric correlation for deformation measurements, the platform must repeat the trajectory within a specified tube (red and blue aircraft above.) Electronical beam steering will compensate for the different aircraft yaw angles between passes. High resolution topographic mapping or tomograhic imaging studies can be supported by flying well defined baselines flying on a trajectory displaced by a spatial baseline from the reference trajectory (purple path.)

3. PLATFORM

The specific requirements for the UAVSAR platform includes considerations such as altitude range, payload weight and accommodation, endurance, combined with the ability to fly a pre specified track very accurately. Also, both the availability and the cost of eventually operating the platform were important considerations.

Our platform requirements specified that the platform should:

- Operate in a variety of weather conditions
- Operate from conventional airports
- Operate above 12,000 meters to avoid commercial traffic and reduce turbulence
- Maintain a flight path with positional accuracy of ±5 meters
- Have a minimum range of 2000 nautical miles
- Have a minimum payload capacity of 300 kilograms
- Have a minimum payload volume of 1 cubic meter
- Have a minimum 2,000 watts of DC power available for the payload
- Support over-the-horizon up/downlink
- Support an external, side-looking, active array antenna (0.5m by 1.6m) without obstruction

The specific requirement to repeat a flight pass, will be discussed briefly below, however a 10 meter operations tube is expected to be required, with the goal of operating within a 1 meter tube a significant fraction of the time. This provides a small repeat-pass baseline desired for deformation measurements as well as an ability to fly the same path multiple times with multiple time scales for reliable acquisition of the desired science data. Flying trajectories this accurately requires real-time platform position knowledge with sub-meter accuracy. Such position accuracy is possible based on previously developed real-time GPS platform position determination capability (20-50 cm) that then must be interfaced with the platform flight management system (FMS).

3.1 Survey of UAV/MPV Capabilities

In our survey of potential UAV/MPV platforms two systems appeared suitable for this application, considering performance requirements and cost constraints, see fig. 2. The operating parameters for the two candidate platforms are listed in Table 1. Both platforms met the criteria specified for the platform including loiter altitude, the true air speed, the range, and the payload weight. Also, both platforms have excess power, mass and volume to meet future needs for upgrading and extending the capabilities of the UAVSAR.

NASA’s Environmental Research Aircraft and Sensor Technology (ERAST) program has conducted some flight tests with both the Proteus UAV and the ALTAIR UAV, basically identical to a Predator-B UAV. Between the two platforms, the Proteus is the larger and more capable platform. However, the Proteus currently requires a two-person crew for landing and takeoff. In addition, there is only one Proteus aircraft available for scientific experiments. Experiments are conducted on a first-come first-serve basis. NASA or other government agencies fund most of the payloads. In early 2000, NASA signed a contract with General Atomics for the development of two enhanced Predator-B UAVs, the ALTAIR, to perform high altitude Earth science missions. Flight tests for the ALTAIR UAV began in the Spring of 2003. The ALTAIR is based on General Atomics Aeronautical Systems, Inc.’s (GA-ASI) family of UAVs with over 35,000 flight hours in deployments for scientific, military, and civil applications.

ALTAIR UAV:
Enhanced Predator-B produced by General Atomics Aeronautical Systems, Inc. for NASA

Proteus Aircraft:
Operated by Scaled Composites in Mojave. One-of-a-kind platform

Figure 2: Two aircraft platforms are currently being considered to host the UAVSAR radar. Altair is a UAV while Proteus is a MPV.

Table 2. Platform Candidates

Plat-form	Alt (m)	Spd (kts)	L (m)	Wings (m)	Rng (nmi)	Pay-load weight (kg)
ALTAIR	13,700	220	8.23	14.84	32 hrs	340
Proteus	19,800	450	17.2	23.6	9,000 24 hrs	900
DC-8	12000	400	47.8	45.1	5400 12 □ □□	∞

In light of the potential desire to replace traditional aircrafts like the NASA DC-8 and ER-2s with UAVs and the Proteus aircraft to support Earth Science missions, our radar design aims at supporting data acquisition on both the ALTAIR UAV and the Proteus aircraft with minimal modifications.

3.2 The "Enhanced" Predator-B Aircraft: The ALTAIR

The ALTAIR is a derivative of the fully operational Predator–B UAV and is developed specifically for scientific and commercial applications that require large payload capacities with operations to 15,850 m (52,000 ft). The jet-powered turboprop ALTAIR can remain airborne for 32 hours. Equipped with fault-tolerant avionics, the ALTAIR is an extremely reliable and stable platform to meet a variety of mission scenarios. The ALTAIR is being developed at GA-ASI's flight operations facility in El Mirage, California adjacent to Edwards Air Force Base, under the supervision of NASA Dryden's ERAST UAV program. From the ALTAIR Experimenter's Handbook we found much of the information needed for our initial design.

The ALTAIR aircraft specifications are:

1) Wingspan: 26.2 m (86 ft)
2) Length: 11.0 m (36.2 ft)
3) Height: 3.6 m (11.8 ft)
4) Maximum payload: 300 kg (660 lb)
5) Maximum altitude: 15,850 m (52,000 ft)
6) Air speed: 60 – 200 knots
7) Endurance: 32 hours above 12,192 m
8) Maximum ferry range: 5170 nm
9) Power: 9 kW main, 4.5 kW backup (The UAV requires 2 kW)
10) Payload bay size: 46 ft^3
11) Safety: triple redundant control module, dual flight controls, dual electrical power systems, Traffic Avoidance and Collision Alert System (TCAS), ATC voice relay, mode 3C transponder, NASA approved flight termination system (FTS).
12) Navigation: remotely-piloted or fully-autonomous with three integrated INU and three Differential GPS units (optional P-code GPS)
13) Data link: C-band line-of-sight, Ku-band SATCOM over-the-horizon, or airborne relay.
14) Shipping size: fits inside a C-130 aircraft (64"W x 437" L x 78" H)
15) Payload bay is not pressurized.

3.3 The Proteus, Minimally Piloted Vehicle

The Proteus aircraft is a very lightweight (6000 lb without payload and fuel) experimental aircraft that requires two pilots (or one pilot and a mission specialist) to operate. The aircraft could become a UAV if more funding is available for further development. Because it is a manned aircraft, the Proteus is certified by the FAA to take off and land at any airport with a 6000-ft runway. However, it does require a large hangar for storage because the lightweight aircraft can be easily damaged by strong winds or heavy storms. The Proteus can fly in most weather conditions that a typical aircraft flies, except for some concern about icing on the wings. The Proteus aircraft is an unusual looking aircraft with a canard configuration and a pair of vertical tailplanes mounted on booms extending back from the rear wing (see Fig. 1). The Proteus specifications are:

1) Aft wingspan: 23.6 m (77.6 ft)
2) Canard span: 16.7 m (54.7 ft)
3) Length: 17.2 m (56.3 ft)
4) Height: 5.4 m (17.6 ft)
5) Maximum payload: 900 kg
6) Maximum altitude: 18,593 m (61,000 ft)
7) Air speed: 220 knots at 13.7 km (45,000 ft)
8) Endurance: 8 to 10 hours (pilot restriction)
9) Maximum ferry range: > 2000 nm
10) Payload power: 11.2 kW (28 V-dc)
11) Payload size: limited by the pod size, which can be as big as 10 m x 1.2 m x 1.2 m
12) Navigation: Garmin GPS receiver and Boeing's GPS stabilized INU with a 1 Hz update rate (attitude is updated at 10 Hz).
13) SATCOM link: via INMARSAT (2400 baud); via Iridium (9600 baud).
14) Standard payload pod is not pressurized. Pressurized pod would double the pod cost.

The Proteus aircraft provides many options for mounting the L-band antenna(s). For a single-antenna system, the most obvious option is to mount the antenna on the side of the payload pod. This will minimize power loss and integration time. For an along-track interferometry system, it is possible to mount two L-band antennas at either end of the 10-m long payload pod to achieve a 7 m physical baseline. Alternatively, the fuselage of the aircraft could provide about a 10 m physical baseline. For single-pass cross-track interferometry, the two antennas could be mounted on either tailplanes on the aft-wings to provide a physical baseline of about 7 m.

A pilot and a co-pilot can only provide limited support to the payload, such as power cycling the instrument. Hence, radar operation has to be completely automated with self-diagnostic capabilities built into the system. A satellite link is available typically via INMARSAT with a low data rate of 2400 baud to provide limited communication with the radar instrument from the ground. On deployment, the Proteus aircraft crew consists of the two pilots and the crew chief (to service the aircraft). Permission to fly over air space is granted by the FAA similar to any manned aircraft, which is logistically easier than the Altair UAV and does not require the 60 day lead time allowing for rapid response to geophysical events of interest.

3.4 Proteus Manual Flight Control Tests

At a flying altitude of 13.7 km (45,000 ft), the Proteus aircraft is currently flown manually by the pilot. The ability to stay within a 10 m tube at this altitude is heavily dependent upon the accuracy of the real-time DGPS (which the Proteus currently does not have) and the skills of the pilot. We conducted an experiment in conjunction with Scaled Composites and NASA Dryden Research Center to assess the ability of a pilot to fly the Proteus within a 10 m tube[3]. We provide a brief description of the results below.

We collected position data for three flight lines approximately 100 km in length (with two of the flight lines orthogonal) at an flight altitude of 45000 ft (13716 m) to see how well the pilots can control the aircraft with varying wind conditions aloft. We modified the real-time GPS equipment developed at JPL to provide the pilot with real-time display of offsets from the desired trajectory. The system was installed on the Proteus aircraft along with a new antenna to receive the GPS correction data needed to get the submeter accuracy that is achieved by the system. We recorded the position data at a 1 Hz rate and obtained 10 Hz attitude angle data recorded by the Proteus telemetry system. The third pass was by far the best pass and was indicative of the pilots learning to fly the aircraft more effectively using the GPS navigation display. However even for this "best track" most of the time the aircraft was outside the required 10 m tube and even was outside a 50 m tube for a large fraction of time. For the third flight line the mean and standard deviation of the error in the cross-track position was 0.9 m and 25.8 m and was 2.0 m and 6.7 m for the vertical position. The pilots indicated that flying the lines using the display was very tiring and that a 3 hour flight was probably about the longest flight a pilot could fly the aircraft that way. Attitude angle variations during the flight lines were very large and would severely impact the ability to generate high quality repeat-pass interferometric measurements.

4. RADAR SYSTEM

The proposed radar for the UAV platform is a miniaturized polarimetric L-band radar for repeat-pass with optional later additions including a second antenna across-track antenna for single-pass interferometry (elevation mapping capability), or a second antenna mounted along-track for along-track interferometry (velocity and current measurements) and additional frequencies of operation. The system will demonstrate key measurements including:

- Precision topography change for monitoring earthquakes both during and after a seismic event, for monitoring volcanic activity and for monitoring human-induced surface change such as subsidence induced by oil or water withdrawal, or other displacements of the surface from tunneling activities.
- Polarimetric interferometry, which can provide NASA with measurements of forest structure and sub-canopy topography.
- Polarimetric tomography, mapping in detail the vertical structure of a vegetated area.

Precise knowledge of motion and location is provided by the high precision INU and real-time differential GPS receivers. Doppler centroid stability can be achieved by along track electronic beam-steering up to ±20º linked to the INU attitude angle measurements. This dictates the radar design to utilize an active array antenna with transmit/receive (T/R) modules and phase shifters with a beam steering angle resolution of better than 1°.

Based on a data file provided by flight planning software, the UAVSAR will automatically initiate data takes at the appropriate locations throughout the flight. This approach was implemented on GeoSAR (a radar interferometric mapping system designed and built by JPL and currently operated by Earthdata International which is hosted on a Gulfstream II aircraft) with good results. Because of the autonomous requirement, this instrument must include BIT (Built In Test) capability and be able to determine failure at the unit level. A modular approach to delineation of logic functions in the instrument will assist in the addition of potential options in the future. Because the instrument is designed for modularity, reconfiguration for the addition of potential options or installation on a different platform should be feasible.

4.1 Operational Modes

The baseline mode for the single antenna UAVSAR implementation, is an L-band Polarimetry (PolSAR) mode. This mode combined with RTI will support not only deformation measurements (zero baseline case) but also high precision elevation mapping (non-zero spatial baseline) and polarimetric interferometry, e.g. for vegetation and volume scattering studies. The baseline system will also support Co-Polarized Monopulse (CoPM) measurements. This means that the signals recorded by either the top and bottom halfs of the antenna can be recorded individually, with in essence provides for a very short baseline interferometric system. In this mode the system will not support a full quad-pol capability, only like (co-) polarized channels are recorded. Finally, the baseline system will support a Multi-Squint Differential IFSAR mode, allowing that the azimuth beam to cycle through multiple aspect angles (e.g. fore, broadside, and aft) on consecutive pulse transmissions. This capability will allow experiments with vector displacement measurements etc.

If the system is optionally augmented with a second antenna, the radar will furthermore support modes for single-pass across-track interferometric data acquisitions, including a Polarimetric Ping-pong Cross Track Interferometry mode (PolXTIP), and single antenna transmit, dual antenna receive modes Polarimetric Cross Track Interferometry (PolXTI1) and Polarimetric Cross Track Interferometry (PolXTI2). The previously mentioned monopulse modes will also be implemented to support modes for single or dual polarization acquisitions, Monopulse Cross Track Interferometry Horizontal Polarization (MXTIH), Monopulse Cross Track Interferometry Vertical Polarization (MXTIV), and Monopulse Cross Track Interferometry Dual Polariztions (MXTIP). Finally, if the second antenna optionally can be mounted along the fuselage relative to the primary antenna, the system will also support a Vector Along Track Interferometry both Polarizations (VATI) mode.

4.2 Radar Electronics

Based on the science objectives and UAV platform characteristics, the key parameters of the radar design include:

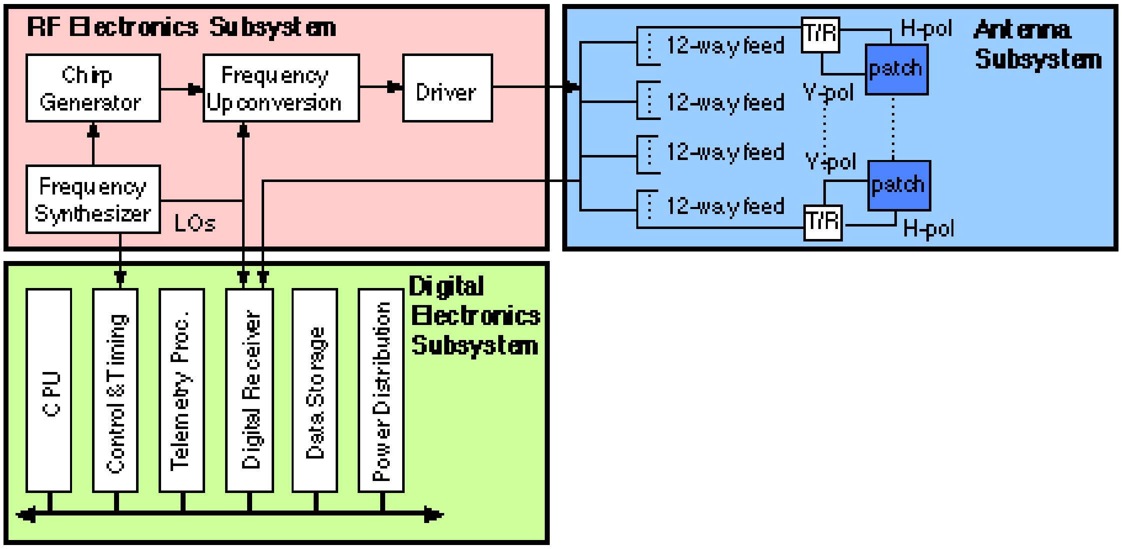


Figure 3: Simplified instrument block diagram of the L-band Repeat-Pass Interferometer.

Frequency:	1.26 GHz (0.2379 m)
Bandwidth:	80 MHz
Pulse duration:	40 msec
Polarization:	Fully polarimetric
Interferometry:	Repeat-Pass
Range swath:	16 km
Look angle:	30º - 60º
Transmitter:	2.0 kW peak power
Antenna size:	0.5 m x 1.6 m with electronic beam steering capability
PRF:	1600 Hz (interleaving H and V transmit polarizations)
Altitude:	13.7 km
Ground speed:	100 m/s

4.3 Hardware Configuration

The radar instrument is made up of three major subsystems: the RF electronics subsystem (RFES), the digital electronics subsystem (DES) and the antenna subsystem. Figure 3 is a simplified instrument block diagram of the L-band radar. The RFES performs the transmit chirp generation, frequency up-conversion, filtering, and amplification during signal transmission. The RFES also controls the routing of the radar signal and the calibration signal. The DES performs overall control and timing for the radar, frequency down-converts and digitizes the received echo, and routes the data to on-board data storage. The dual-channel digital receiver employs two high-speed analog-to-digital converters (ADCs) capable of handling L-band signals. Digital filters implemented on field-programmable gate arrays (FPGAs) provide range subband filtering. This approach saves cost, mass, and power while provides tremendous flexibility in the frequency selection of the digital filters. The sub-harmonic sampling technique is frequently used in the communication industry at lower frequencies. The recent availability of high-speed ADCs capable of handling L-band signals makes this technique feasible for radar applications, but has not yet been demonstrated with SAR systems.

The antenna subsystem performs beam steering, transmission, and high power amplification on transmit and low noise amplification on receive. The antenna is a dual-polarization corporate-fed planar phased-array with 2 x 12 T/R modules and phase shifters for electronic beam steering from radar pulse to pulse. The peak transmit power for each T/R module is 80–100 W and the combined power of the 24 T/R modules is approximately 2.0 kW. Typical efficiency for L-band solid state amplifiers (SSPAs) is 40 %. On the transmit end, there will be a polarization switch to direct the transmit signal to either the H or V-polarization feed of the antenna element. On the receive end, each T/R module will have two receiver front-ends (pre-select filter, high power limiter, and low-noise amplifier) to accommodate radar echoes from both the H and V-polarizations.

4.4 Estimate of Power, Weight, Volume

The estimated DC power for the L-band polarimetric RTI is just under 1 kW when the radar is transmitting. This is well within the capacity of the ALTAIR UAV or the Proteus aircraft. The standby DC power should be on the order of 150 W. The active array antenna should weigh less than 80 kg since each T/R module weighs about 0.5 kg. The remainder of the radar electronics in the payload bay should weigh less than 100 kg (approximately 20 kg for the RFES, 30 kg for the DES, and 30 kg for cabling, power distribution, etc.).

4.5 L-band Cross-Track Interferometry Option

For the Proteus aircraft, L-band cross-track interferometry may be achieved by mounting the two antennas on the tailplanes on the aft-wings to provide a physical baseline of about 7 m to achieve a height accuracy of about 2 m. Likewise L-band cross-track interferometry may be supported on the ALTAIR by placing two antennas at the hard points underneath the wings, which are 3.7 m apart. The expected height accuracy should be better than 3 m, which is a significant improvement from the AIRSAR's L-band interferometer height accuracy of 5 to 10 m. Polarimetric XTI may be achieved if both the antennas are dual-polarized and H & V polarized pulses are transmitted in an interleaving manner.

4.6 L-band Along-Track Interferometry Option

L-band along-track interferometry may be achieved by placing two antennas at the front end and tail end of the platform respectively. For the ALTAIR, the maximum physical baseline is 3 to 4 m depending on the length of the antenna. This is significantly shorter than the AIRSAR's physical baseline of 20 m and is not likely to be a viable mode for this platform. For the Proteus aircraft, the physical baseline is 7 to 10 m depending on whether we mount the antenna pairs on the payload pod or the fuselage of the aircraft. This antenna separation is nearly optimal for L-band ATI given the platform speed of 100 m/s for the Proteus. Addition of a second frequency radar would be more involved than the addition of an interferometric capability. For the second frequency radar, it would be necessary to add: An additional Up-Converter unit, an additional Switching Network, an additional antenna panel, a pair of additional receivers for down-conversion and a pair of additional digital channels to the digital system. This option could be implemented in the Proteus aircraft without modifying the anticipated mechanical packaging approach. In order to implement this option in the Predator-B aircraft, it is quite possible that a more efficient mechanical packaging approach would need to be pursued.

4.7 High Frequency Cross-Track Interferometry Option

High frequency XTI (e.g. X/Ku/Kax-band) and polarimatric capability are key components of the hydrology discipline, which could be used to measure snow wetness, river level changes, etc and cold land processes, which could be used for ice thickness and ice age determination. This capability would require a pair of antennas, a pair of receiver front-ends to down-convert the signal to an L-band signal, an additional pair of L-band digital receivers, an additional chirp generator card with frequency up-conversion to the desired frequency, and added on-board data storage.

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